Silent Failure Localization on Optical Transport System

Hiroki Date, Takashi Kubo, Takeshi Kawasaki, and Hideki Maeda

***Abstract*— A silent failure is a kind of failure that existing optical devices or equipment cannot detect although the failure actually happens. This failure makes it more difficult for maintenance operators to identify the fault point, which potentially deteriorates the reliability of the network. To address this issue, we propose a unique silent failure localization method using characteristic information obtained from the optical devices and equipment. As an example of the silent failures, a wavelength selective switch (WSS) failure is studied, and we propose a detection and localization scheme based on the method to use in a WSS failure scenario. Results of a field experiment revealed that the proposed scheme properly localize the fault point with an accuracy of within 4%.**

***Index Terms*— Failure analysis, optical communication, optical communication equipment, silent failure.**

I. Introduction

OPTICAL transport systems need to handle higher capacity due to the rapid increase of internet traffic [1]. As capacity grows, key optical devices such as optical amplifier (AMP) and wavelength selective switch (WSS) also need higher reliability and stability because optical signals carrying terabits of data flow into those devices. Failures in such devices significantly impact the whole network, which might lower the quality of service. To reduce the impact on the network, maintenance operators continuously check alarms and warnings raised from network elements. When failures are found, the operators take immediate actions to restore them by localizing the point in accordance with alarms and warnings. However, there are cases in which neither the network elements nor any devices can detect alarms even though the failures actually happen. Such failure patterns are called “silent failures.” Once a silent failure happens, maintenance operators have no way to identify the problem until they receive complaints from customers. Even when they find out that a failure has occurred somewhere in the network, localizing the failure point incurs a huge amount of time as well as human resources. To address this issue, several studies have used information correlation on multi-layer networks including IP networks [2], but this approach is not easy to implement in real time manner since maintenance operation is usually vertically divided layer by layer in the network. In this letter, we propose a unique silent failure localization method by using information only from the optical transport system. In this method, characteristic information of optical signals is collected from a digital signal processor (DSP) and other optical devices in the receiving end transponders. Some similar methods utilize the signal-to-noise ratio (SNR) with estimations of end-to-end optical channels using machine learning or an analytical model such as Gaussian noise to localize anomalies [3], [4] or utilize nonlinear and dispersion coefficients using digital backpropagation to localize optical excess loss points [5]. The proposed method can be potentially used to cover a wide range of failure patterns that may occur in the optical transport network by utilizing various parameters. To examine the effectiveness of the proposed method, a field experiment was conducted under a WSS failure scenario. The results revealed that utilization of chromatic dispersion (CD) can help to correctly localize the failure point.

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II. Problems of Silent Failures

As noted in the previous section, a silent failure is a cumbersome problem for network maintenance operators. This type of failure occurs only when specific conditions are met, so it is quite infrequent. However, silent failures will become critical issues when the scale of the optical transport network becomes larger. As an example of silent failures, a WSS failure pattern can be assumed. A typical optical cross connect node consists of some pairs of an optical splitter and a WSS for each direction. Received optical signals are split into ports: some are for drop and the others are for other direction WSSs (pass through). The WSS switches and filters incoming optical signals from add ports and from the other direction splitters. Assuming that WSS uses a micro electro mechanical system (MEMS) based optical switch, a malfunction in the voltage control system may lead to a wrong connection. Optical signals may connect the wrong transponder at the receiving end if the wrongly connected path used the same wavelength as the correct path. In this case, no alarms are detected from transponders or the optical cross connect node. Therefore, maintenance operators cannot find out about the failure until customers complain.

III. Proposed Silent Failure Localization Method

We propose a silent failure localization method to localize silent failures and restore them immediately. Our approach [6] is as follows:

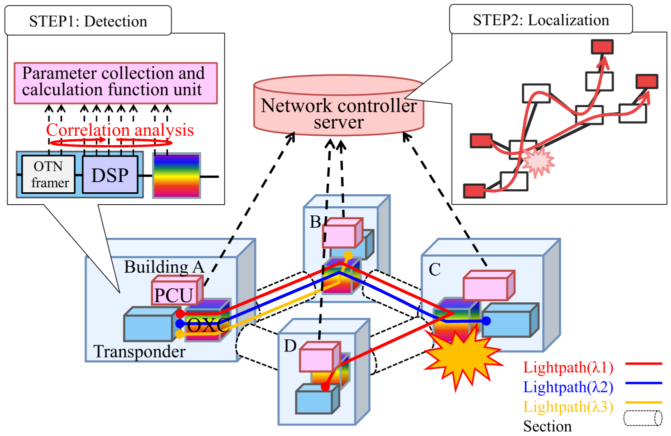

Fig. 1. Proposed localization method.

- To increase information for failure analysis, the method collects characteristic information of optical signals from DSP on receiving end transponders.
- To trace several important parameters of characteristic information with high scalability, the method utilizes correlation among the parameters.
- The method estimates the failure location by using factors estimated from the correlation, network topology, and route information of each optical path.

The proposed method takes two steps as shown in Fig. 1: failure detection and cause estimation (STEP 1) and failure localization (STEP 2). In this method, the parameter collection and calculation function unit (PCU) is deployed on each piece of optical transport equipment, and the failure localization function unit is deployed on a controller server. This approach can increase scalability by limiting the amount of data transfer and computing resources for analysis at the network controller server.

In STEP 1, a failure is detected and its cause is estimated. The PCU continuously collects characteristic information from DSP on receiving end transponders and analyzes correlations among them so that it extracts temporal fluctuation patterns. The PCU judges whether an anomaly exists or not and estimates causes based on the correlation analysis results and fluctuation patterns. The PCU notifies the controller server of the estimated causes and the suspected optical path.

In STEP 2, failure localization is performed. The controller narrows down the failure coverage area by an optical path or section unit based on the notified results in STEP 1 and the network topology and route information of optical paths. The controller identifies suspected optical transport network equipment by using the determined failure coverage area, the estimated causes, and configuration information of each type of equipment.

IV. Field Experiments

We conducted field experiments to evaluate whether the proposed method can work in a WSS silent failure scenario, which actually occurred on a commercial system. Based on the assumed WSS silent failure scenario, WSS selects a wrong port due to a malfunction inside the WSS, resulting in a wrong connection being made between the wrong pair of transponders. A detection and localization scheme is studied in this case.

A. Detection and Localization Scheme for WSS Failure Scenario

The wrong route after the WSS failure can be estimated by using accumulated CD gathered from DSP of receiving end transponders. Assuming CD is uniform in entire fibers, the distance can be estimated as Eq. (1).

$$D = \frac{K}{F}, \quad (1)$$

where D [km] denotes the distance of the whole optical path, K [ps/nm] denotes the accumulated CD on whole optical path, and F [ps/nm/km] denotes the assumed CD of whole fiber with the used wavelength. Therefore, fluctuations of the accumulated CD measured at receiving end transponders can be used to detect route changes of optical paths due to the WSS failure. In addition, the controller has route information of each optical path, so the proposed method can localize the WSS failure by identifying the branch point where the wrong route after the failure and the correct route to the receiving end crossed. The route can be estimated by using the fiber distance of each section measured in advance as Eq. (2).

$$\begin{aligned} &\mathit{minimize}\ \left| D - \sum\nolimits_{(i,j)\in E} C_{ij} X_{ij} \right|, \\ &\text{s.t.}\ \sum\nolimits_{(s,i)\in E} X_{si} - \sum\nolimits_{(i,s)\in E} X_{is} = 1, \\ &\quad \sum\nolimits_{(t,j)\in E} X_{tj} - \sum\nolimits_{(j,t)\in E} X_{jt} = -1, \\ &\quad \sum\nolimits_{(i,j)\in E} X_{ij} - \sum\nolimits_{(j,i)\in E} X_{ji} = 0, \quad X_{ij} \in \{0,1\}, \quad (2) \end{aligned}$$

where C_{ij} denotes the distance between nodes i and j, X_{ij} denotes a Boolean that is 1 if the optical path passes through the fiber between i and j and 0 if not, E denotes the set of all links, s denotes the start node of the optical pass, and t denotes the end node of the optical pass.

Identifying one branch point is best, but there will be multiple candidate branch points in rare cases. In those cases, we can finalize the failure point by inspecting each WSS remotely and on site. This refinement process is also very effective for operators. We evaluate the identification accuracy in the next section.

B. Field Experiments

We conducted field experiments to evaluate the proposed method. We confirmed the effect of the assumption that CD is uniform in all laid fibers and then evaluated the accuracy of route estimation after the WSS failure because the accuracy of the detection and localization depends on that of the route estimation derived from Eq. (1). The experimental setup is shown in Fig. 2. The transponder and erbium-doped fiber AMPs (EDFAs) were deployed in building 1, and fibers were looped in building 2. All fibers were single-mode fibers, and the distance of a round trip between buildings 1 and 2 was 112.2 km as a section. We manually simulated the WSS failure at building 1 to change the optical path route from two sections

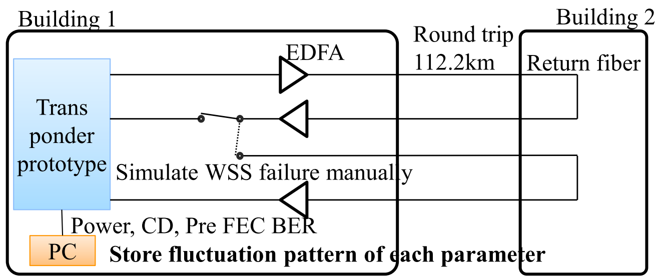

Fig. 2. Experimental setup.

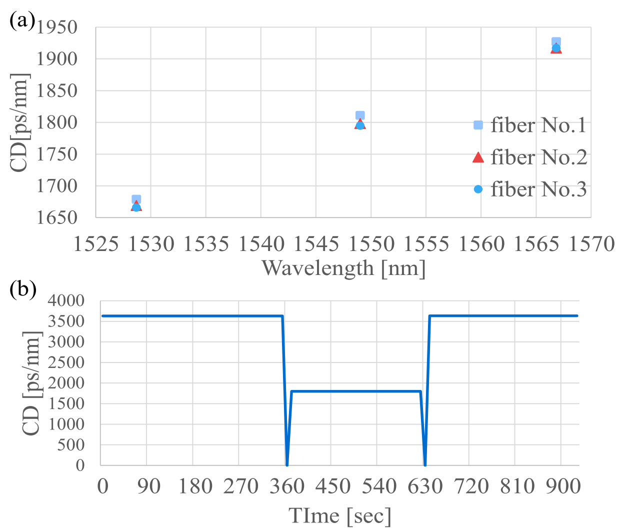

Fig. 3. Experimental results: (a) accumulated CD on three fibers varying wavelength, (b) accumulated CD where simulated WSS failure.

to one section and then collected characteristic information of optical signals including accumulated CD.

First, we evaluated the relationship among CD, wavelength, and individual differences of actual laid fibers to determine the effect of the assumption that CD is uniform on laid fibers. Fig. 3(a) shows the measured accumulated CD on a section with three fibers that were selected randomly. The differences in accumulated CD among the fibers were less than 1% at any wavelength, so the effect of the assumption is small enough to detect the failure and estimate the route even with actual laid fibers.

Next, we evaluated the accuracy of the detection and the route estimation after the WSS failure. Fig. 3(b) shows the accumulated CD where we simulated the WSS failure. The wavelength of the optical path was 1549.01 [nm]. The route was switched from two sections to one section between 360 [sec] and 630 [sec] as the simulated WSS failure. We can see accumulated CD fluctuation in which the value was changed from 3629 [ps/nm] to 1800 [ps/nm] after the simulated WSS failure. During the simulated WSS failure, the route distance was estimated to be 108.1 [km] by using Eq. (1) and average CD of fibers, which is 16.65 [ps/nm/km], measured in advance. The difference between the actual and estimated distances was 4.1 [km] and less than 4%. The measurement difference is considered to occur due to temperature, frequency offset, or polarization mode dispersion. In Woodward *et al.* [7], the difference was less than 4.6% over 95% of the time. The Japan Photonic Network Model [8], which estimates Japanese core network topology, has 82 links. Their average is 153.8 [km] and standard deviation is 123.8. In addition, USANet [9] for the US network topology has 43 links whose average is 993.0 [km] and standard deviation is 367.8. PanEuro [9] for the European network has 41 links whose average is 625.4 [km] and standard deviation is 263.0. Optical paths are composed by several links, so the trend of differences in the distance among optical paths is considered to become larger although it depends on path accommodation design. Therefore, we can say that the detection and the route estimation are accurate enough to detect and localize the WSS failure in many cases of path accommodation design on an optical transport system.

V. CONCLUSION

We proposed a silent failure localization method on an optical transport system utilizing characteristic information of an optical path in order to restore silent failures immediately. In addition, we proposed a wavelength selective switch (WSS) failure localization method to detect and localize a WSS failure that had occurred on an actual commercial system. The proposed detection and localization procedures by measured accumulated chromatic dispersion (CD) were evaluated in field experiments, and the results showed they can be applied on actual laid fibers with less than 4% measurement difference.

In the future, we will expand the proposed method to localize silent failures more accurately and handle other failure modes by using other characteristic information. We will also expand it to predict failures using machine learning with collected information of optical paths to enable it to handle failures in advance.

REFERENCES

[1] H. Maeda, H. Kawahara, K. Saito, T. Seki, T. Sasai, and F. Hamaoka, "Real-time demonstration of 500-Gbps/lambda and 600-Gbps/lambda WDM transmission on field-installed fibers," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3.

[2] R. R. Kompella, J. Yates, A. Greenberg, and A. C. Snoeren, "Detection and localization of network black holes," in *Proc. IEEE INFOCOM 26th IEEE Int. Conf. Comput. Commun.*, May 2007, pp. 2180–2188.

[3] S. Barzegar *et al.*, "Soft-failure localization and device working parameters estimation in disaggregated scenarios," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3.

[4] Q. Fan *et al.*, "Experimental comparisons between machine learning and analytical models for QoT estimations in WDM systems," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3.

[5] T. Sasai *et al.*, "Simultaneous detection of anomaly points and fiber types in multi-span transmission links only by receiver-side digital signal processing," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3.

[6] T. Kubo, H. Yamamoto, H. Kawahara, T. Seki, T. Oka, and H. Maeda, "Failure localization in optical transport networks," presented at the 15th iPOP, Kawasaki, Japan, May 2019.

[7] S. L. Woodward *et al.*, "Characterization of real-time PMD and chromatic dispersion monitoring in a high-PMD 46-Gb/s transmission system," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2048–2050, Dec. 15, 2008.

[8] *Technical Committee on Photonic Network. JPN Model.* Accessed: Sep. 24, 2020. [Online]. Available: https://www.ieice.org/cs/pn/jpn/JPNM/JPNM_v20161013sn(E).zip

[9] L. R. Costa, I. B. Brasileiro, and A. C. Drummond, "Low margin QoT-aware RMLSA with circuit invigoration in elastic optical networks," in *Proc. GLOBECOM IEEE Global Commun. Conf.*, Dec. 2020, pp. 1–6.